

# Higgs boson production via vector-like top-partner decays: diphoton or multilepton plus multijets channels at the LHC

A. Azatov,<sup>1</sup> O. Bondu,<sup>2</sup> A. Falkowski,<sup>3</sup> M. Felcini,<sup>4</sup> S. Gascon-Shotkin,<sup>2</sup>  
D. K. Ghosh,<sup>5</sup> G. Moreau,<sup>3</sup> A. Y. Rodríguez-Marrero,<sup>4</sup> and S. Sekmen<sup>6</sup>

<sup>1</sup>*Dipartimento di Fisica, Università di Roma “La Sapienza”, INFN Sezione, I-00185 Roma, Italy*

<sup>2</sup>*Université de Lyon, Université Claude Bernard Lyon 1, CNRSIN2P3,  
Institut de Physique Nucléaire de Lyon, F-69622 Villeurbanne Cedex, France*

<sup>3</sup>*Laboratoire de Physique Théorique, Bât. 210, CNRS,  
Université Paris-sud 11, F-91405 Orsay Cedex, France*

<sup>4</sup>*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, E-39005 Santander, Spain*

<sup>5</sup>*Department of Theoretical Physics, Indian Association for the Cultivation of Science Kolkata 700 032, India*

<sup>6</sup>*CERN Physics Department, CH-1211 Geneva 23, Switzerland.*

We first build a minimal model of vector-like quarks where the dominant Higgs boson production process at LHC – the gluon fusion – can be significantly suppressed, being motivated by the recent stringent constraints from the search for direct Higgs production over a wide Higgs mass range. Within this model, compatible with the present experimental constraints on direct Higgs searches, we demonstrate that the Higgs ( $h$ ) production via a heavy vector-like top-partner ( $t_2$ ) decay,  $pp \rightarrow t_2 t_2$ ,  $t_2 \rightarrow th$ , allows to discover a Higgs boson at the LHC and measure its mass, through the decay channels  $h \rightarrow \gamma\gamma$  or  $h \rightarrow ZZ$ . We also comment on the recent hint in LHC data from a possible  $\sim 125$  GeV Higgs scalar, in the presence of heavy vector-like top quarks.

## I. INTRODUCTION

One of the primary goals of the Large Hadron Collider (LHC) is the direct search for the cornerstone of the Standard Model (SM), namely the Higgs boson, or for any signal from alternative Electro-Weak Symmetry Breaking (EWSB) mechanisms. The SM is probably not the ultimate model of nature. It is clear that new channels for Higgs production, that can arise in extensions of the SM, would have profound impact on the discovery of a Higgs boson, while providing insight in the physics beyond the SM. An attractive possibility is the Higgs production in decays of additional heavy colored particles that can be copiously pair produced at the LHC via strong interactions.

Within well-motivated theories beyond the SM, there are some candidates for such new heavy colored states, extra quarks with vector-like couplings, whose existence is predicted by most of the alternatives to supersymmetry. In this context, to maintain a naturally light Higgs boson, divergent quantum corrections from loops of the top quark are often canceled by top-partner contributions [1–3]. Let us describe important examples here. In the so-called little Higgs scenarios, the vector-like quarks arise as partners of the SM fields being promoted to larger multiplets. In the composite Higgs [4–8] and composite top [4–9] models, the vector-like quarks are excited resonances of the bounded states constituting the SM particles. In the extra-dimensional models with (SM) quarks in the bulk, the vector-like quarks are prevalent as Kaluza-Klein (KK) excitations of those bulk fields [10] like in the Gauge-Higgs unification mechanism (see e.g. Ref. [11, 12]) or in the Randall-Sundrum (RS) scenario [13–15] – where some of those KK excitations, the so-called custodians, can be as light as a few hundred’s of GeV [16–21]. Another example is a gauge coupling unification theory where vector-like quarks are embedded into the simplest SU(5) representations [22].

Vector-like quarks with same electric charge as the up-type quarks are often called top-partners (noted  $t'$ ) as these new heavy states mix in general predominantly with the top quark – due to the large top mass and to the related feature that the top quark is in general more intimately connected to ultraviolet physics, like e.g. in composite Higgs models. A  $t'$  can also be called a top-partner in the sense that it is contained in the same group representation as the top quark with respect to symmetries, like the approximate global symmetry of the little Higgs models [1–3], the gauge unification symmetry [22] or the custodial symmetry of RS versions with bulk matter [16–21] (explaining the SM fermion mass hierarchies [23–39]).

At this level, one must mention that the phenomenology of the search for direct production of vector-like quarks at the LHC has been studied from a model-independent point of view in Ref. [40–45] but also in specific frameworks such as the little Higgs models (versions sufficiently safe from EW precision constraints) [46–50] or the composite Higgs hypothesis [51, 52] and the dual RS context [11, 53–58]. These past searches focus generally on the discovery of the vector-like quarks, rather than using these extra quarks to enhance the discovery and identification potential for other unknown particles such as Higgs scalars.

In relation to Higgs detection, there exist studies utilizing the possible Higgs production through vector-like quark decays, as described in the following. Indeed, it is well known since some time [59, 60] that vector-like quark production could be a copious source of Higgs bosons (a possible Higgs factory).

Relatively light Higgs bosons produced from the decay of top-partners can be highly boosted and good candidates for analyses based on jet substructure. This method has been applied [61] for a  $\sim 130$  GeV Higgs decaying to  $b\bar{b}$  at the 14 TeV LHC to improve the Higgs identification capability and reduce the background. In the simple model considered there, the  $t'$  is a singlet under the SU(2)<sub>L</sub> gauge group, which determines the  $t'$  couplings and its tree level

decays into the Higgs boson and the two EW gauge bosons  $t' \rightarrow th$ ,  $t' \rightarrow tZ$ ,  $t' \rightarrow bW$ .

The top-partner can also be singly produced which leads to different final states as compared to the pair production; because of the phase space suppression, the single production becomes competitive with the pair production at a high  $t'$  mass, depending upon the considered model (since the involved  $t'$  couplings to  $h, Z^0, W^\pm$  are fixed by the  $t'$  quantum numbers) [98]. The reconstruction of the Higgs boson produced in the  $t'$  decay, itself singly produced at the 14 TeV LHC, was studied in Ref. [62] assuming the Higgs mass known (to be 120 GeV) and focusing on the channel  $h \rightarrow b\bar{b}$  – with the combinatorial background only. This was performed for a singlet  $t'$  in the “Littlest Higgs” model with the asymptotic branching ratio values of the high  $m_{t'}$  regime:  $B_{t' \rightarrow th} = 25\%$ ,  $B_{t' \rightarrow tZ} = 25\%$ ,  $B_{t' \rightarrow bW} = 50\%$  (from the EW equivalence theorem).

Similarly, a vector-like colored  $b'$  state produced at the 14 TeV LHC can act as a Higgs factory thanks to its decay  $b' \rightarrow bh$ . It was shown [22] that a Higgs mass reconstruction can be obtained with a limited accuracy, concentrating on the decay  $h \rightarrow WW$  ( $W \rightarrow l\nu$ ) for  $m_h = 200$  GeV and assuming the  $m_{b'}$  value to be deduced from a preliminary analysis based on the more appropriate channel  $b' \rightarrow bZ$ . Theoretically, the  $b'$  was originating from the upper component of a  $SU(2)_L$  doublet so there was no significant channel  $b' \rightarrow tW$ .

Higgs mass reconstructions via  $t'$  and  $b'$  decays were also studied for the 14 TeV LHC, based on a light Higgs decaying to  $b\bar{b}$  in the basic models with a unique extra  $t'$  and/or a unique extra  $b'$  [44].

In the present paper, we use the pair production and decay of a vector-like top to develop new search strategies for Higgs boson discovery and mass measurements in the  $h \rightarrow \gamma\gamma$  (diphoton) and  $h \rightarrow ZZ$  channels. We consider  $t'$  masses up to  $\sim 800$  GeV, so that the  $t'$  single productions (involving a model-dependent coupling) are generally subleading compared to the  $t'$  pair production not yet significantly suppressed by phase space factors [99]. The original theoretical and illustrative model considered here, including two top-partners, is constructed to allow interesting interpretations correlating the indirect (via vector-like top decay) and direct Higgs production searches at the LHC, as described in the following. A few characteristic parameter sets – with vector-like top mass in the range between  $\sim 400$  and  $800$  GeV – are chosen as benchmark points avoiding too large  $t'$  contributions to the Higgs rates (constrained by present LHC data) and simultaneously allowing for significant branching fraction values ( $\gtrsim 10\%$ ) of the vector-like top decay to the Higgs boson.

Assuming the presence at low-energy scales only of extra vector-like quark multiplets containing some  $t'$ , we have elaborated a minimal model allowing to strongly suppress the Higgs production via gluon fusion, as compared to the SM. In this simple but non-trivial model, the  $gg \rightarrow h$  cross section suppression factor possibly reaches values below  $10^{-1}$  at hadron colliders; this is to be put in contrast with the  $t'$  representations taken usually in the RS scenario [21, 63–66] [100] and with minimal supersymmetric theories for which such a suppression is not possible to obtain (see respectively Ref. [21, 63] and Ref. [67]). The chiral case of a fourth quark generation can even only increase considerably the gluon fusion rate.

The illustrative minimal  $t'$  model suggested here is interesting in the sense that it can easily lead to the following interpretations: for example, a 255 GeV Higgs is excluded in the SM by the present LHC results [68, 69] but can still exist in the above minimal SM extension with  $t'$  where the reduced Higgs production cross section can be below the LHC upper limits. In other words, the Higgs boson would really be light but not detectable with the present luminosity/energy, via conventional channels. A channel that could then allow the Higgs discovery would be through the  $t'$  pair production and decays, as illustrated in this paper. Another possibility is that the slight excess of events observed in data for a Higgs mass hypothesis of  $\sim 125$  GeV [70, 71] is confirmed by the 2012 searches at the LHC. Then the measured Higgs production cross section times branching ratios could certainly be reproduced by the present  $t'$  model, given the parameter freedom in this model and its capability of inducing large Higgs rate corrections of both signs. Then investigating this additional Higgs production channel as the  $t'$  decay, as discussed here, would of course be relevant in particular to confirm the Higgs existence. Finally, in the case of a signal from a heavy Higgs, say above 500 GeV [101] as we will consider here, the same fit of Higgs data would be instructive as a test of the present  $t'$  model and similarly the  $t'$  decay should be considered as a complementary channel of Higgs production.

## II. THE THEORETICAL MODEL

At low scale, let us assume the presence of a unique additional vector-like quark multiplet including a  $t'$  component. Then, irrespective of the representation of this multiplet under the  $SU(2)_L$  gauge group (i.e. the  $t'$  belongs to a singlet, doublet, ...), the interferences between the next heavier top mass eigenstate  $t_2$  [composed of  $t, t', t''$ ] and the  $t_1$  [ $\equiv$  the physical top quark whose mass is measured] contributions [102] to the triangular loop of the gluon-gluon fusion mechanism will be systematically constructive. This is due to the fact that the physical signs of the Yukawa coupling and mass insertion involved in this loop – two chirality flips are necessary – will be systematically identical giving rise to a positive product (for  $t_1$  as well as for  $t_2$ ). Hence, the cross section of the gluon fusion mechanism may be increased or slightly decreased (because of a possible  $t$  Yukawa coupling reduction) relatively to the SM case. To get the minimal scenario with only additional vector-like quark multiplets including  $t'$  components able to strongly suppress the gluon fusion, one needs to introduce a first top-partner  $t'$  in a  $SU(2)_L$  doublet as well as a second top-partner  $t''$  in a gauge singlet. For simplification, we do not consider the doublet including a  $b'$  [103] that would also

be exchanged in the triangular loop. So we end up with the doublet  $(q_{5/3}, t')$ ,  $q_{5/3}$  being an exotic quark with electric charge 5/3 and without self-Yukawa coupling (in turn no possible loop exchange). Indeed, with this field content, all the possible generic mass terms and Yukawa couplings appearing in the Lagrangian are,

$$\begin{aligned} \mathcal{L}_{\text{Yuk.}} = & Y \overline{\begin{pmatrix} t \\ b \end{pmatrix}}_L H^\dagger t_R^c + Y' \overline{\begin{pmatrix} q_{5/3} \\ t' \end{pmatrix}}_L H t_R^c + Y'' \overline{\begin{pmatrix} q_{5/3} \\ t' \end{pmatrix}}_{L/R} H t_{R/L}'' + \tilde{Y} \overline{\begin{pmatrix} t \\ b \end{pmatrix}}_L H^\dagger t_R'' \\ & + Y_b \overline{\begin{pmatrix} t \\ b \end{pmatrix}}_L H b_R^c + m \bar{t}_L' t_R^c + m' \overline{\begin{pmatrix} q_{5/3} \\ t' \end{pmatrix}}_L \begin{pmatrix} q_{5/3} \\ t' \end{pmatrix}_R + m'' \bar{t}_L' t_R'' + \text{H.c.} \end{aligned} \quad (1)$$

where  $H$  represents the SM Higgs doublet and  $L/R$  the fermion chiralities. By construction, the vector-like quarks possess same quantum numbers and gauge group representations for the left-handed and right-handed states. We have not written the Yukawa couplings for the first two quark generations as their mixings with the top-partners  $t', t''$  are negligible compared to the  $t$ - $t'$ - $t''$  mixing and the CKM mixing angles are typically small, so that the first two quark generations are decoupled from  $b, t, t', t''$ . Note that a field redefinition rotating  $t_R^c$  and  $t_R''$  can allow to eliminate the  $m$  term without loss of generality. A last remark is that the  $Y''$  term could be split in two terms with different chiralities and coupling constants. The Lagrangian (1) gives rise, after EWSB, to this top mass matrix:

$$\mathcal{L}_{\text{mass}} = \overline{\begin{pmatrix} t \\ t' \\ t'' \end{pmatrix}}_L \begin{pmatrix} Yv & 0 & \tilde{Y}v \\ Y'v & m' & Y''v \\ m & Y''v & m'' \end{pmatrix} \begin{pmatrix} t^c \\ t' \\ t'' \end{pmatrix}_R + \text{H.c.} \quad (2)$$

with  $v \simeq 174$  GeV the SM vacuum expectation value of the Higgs boson. In our notations of Eq.(2), the parameters  $Y, Y', Y''$  and  $\tilde{Y}$  contain the whole sign (i.e. the combination of the  $\text{SU}(2)_L$  contraction signs and Yukawa coupling constant signs). Note that vector-like fermions do not require EWSB to acquire mass. The non-trivial consequence of the present  $t', t''$  charge assignment choice is the presence of Yukawa terms in the block diagonal matrix of Eq.(2) associated to the top-partners [104] (such Yukawa matrix elements would be absent in the first case of a unique top-partner). This feature of the mass structure allows strong suppressions of the gluon fusion mechanism. In particular, the own top-partner ( $t', t''$ ) Yukawa coupling ( $Y''$ ) sign can be chosen independently of the top ( $t$ ) Yukawa coupling ( $Y$ ) sign in order to generate destructive interferences between the top and top-partner loops.

### III. $t_2$ RATES AND DIRECT CONSTRAINTS

We consider here the model described in the previous section, where  $t', t''$  denote the states in the interaction basis while  $t_1, t_2$ , and  $t_3$  stand for the mass eigenstates, with  $m_{t_3} > m_{t_2} > m_{t_1}$ ,  $t_1$  being the standard top quark and  $m_{t_1}$  its physical mass. We concentrate on the phenomenology of the next-to-lightest top mass eigenstate  $t_2$ ; the  $t_3$  eigenstate production is sub-dominant given its larger mass. In a second stage, one could add the contributions to the Higgs production from the  $t_3$  decays like  $t_3 \rightarrow t_1 h$  or  $t_3 \rightarrow t_2 Z$ .

In Table I, we define our benchmark points by the values of the fundamental parameters – including the Higgs mass  $m_h$  – and the corresponding  $m_{t_2}, m_{t_3}$  values. These sets of parameters are selected in particular to have a large branching fraction  $B_{t_2 \rightarrow t_1 h}$  enhancing the studied Higgs signal. Note that in the minimal model with a unique doublet  $(q_{5/3}, t')$ ,  $B_{t_2 \rightarrow bW}$  is negligible compared to  $B_{t_2 \rightarrow t_1 h}$  and  $B_{t_2 \rightarrow t_1 Z}$  [44]. For none of the considered benchmark points, the channel  $t_2 \rightarrow q_{5/3} W$  is open. Table I also provides the theoretical  $t_2$  widths and the  $\sigma_{t_2 t_2}$  cross sections for the  $t_2$  pair production at LHC computed with the HATHOR program [72] at NNLO. As a comparison, we give also in Table I the expected SM cross sections [73] for Higgs production via gluon fusion,  $\sigma_{\text{gg} \rightarrow h}^{\text{SM}}$ . It is physically important to note that the branching ratios  $B_{t_2 \rightarrow t_1 h}$  and  $B_{t_2 \rightarrow t_1 Z}$  are not vanishing in contrast with the case of a fourth generation  $t'$  quark so that the observation of such decays (discussed in Section VI) would even prove the vector-like nature of a heavy top-like quark.

Table I presents finally the CMS constraints on the observables  $\sigma_{t_2 t_2} B_{t_2}^2$  derived from the search for pair production of a heavy top-like quark [68, 74, 75] (present bounds from ATLAS are less stringent [69, 76]). It appears that the corresponding theoretical values, predicted in the models considered here, respect those experimental limits for  $m_{t_2}$  as low as  $\sim 400$  GeV [105]. Increasing theoretically  $B_{t_2 \rightarrow t_1 h}$ , and consequently lowering  $B_{t_2 \rightarrow t_1 Z}$  and  $B_{t_2 \rightarrow bW}$ , is allowed within these constraints.

Due to these lower limits on  $m_{t_2}$  typically around 400 GeV, the  $t_2$  pair production suffers from a significant phase space suppression so that the whole rate for a single Higgs production through the  $t_2$  decay is smaller than for the standard gluon fusion mechanism; there is e.g. a factor of  $\sim 10$  for point A1 at 14 TeV, as shown the Table I. However, the number of Higgs events issued from the  $t_2$  decay can be significant at 14 TeV with suitable luminosities. This Higgs production channel can thus be an interesting Higgs boson (and  $t_2$ ) discovery channel, among others, and especially in cases where the gluon fusion mechanism is suppressed by the presence of  $t', t''$  states, as it occurs for instance with point B (see Table I).

Parameter Set	A1	A2	B	C	D
$Y / \tilde{Y}$	-1.43 / 2	1.02 / -0.1	1.15 / 0.4	1.12 / -0.5	1.05 / -0.3
$Y' / Y''$	1.85 / -1	1 / 0.55	-1.5 / 1.6	1.1 / 1.65	1.7 / 1.9
$m / m' \text{ (GeV)}$	0 / 370	0 / 675	0 / 770	0 / 810	80 / 1100
$m'' \text{ (GeV)}$	510	645	980	850	1100
$m_{t_3} \text{ (GeV)}$	722	804	1181	1125	1454
$m_{t_2} \text{ (GeV)}$	403	599	626	572	788
$m_h \text{ (GeV)}$	125	125	255	320	540
$\sigma_{gg \rightarrow h}^{\text{SM}} \text{ (pb) @ 7 TeV}$	15.31	15.31	3.18	2.25	0.58
$\sigma_{gg \rightarrow h}^{\text{SM}} \text{ (pb) @ 14 TeV}$	49.85	49.85	13.50	10.59	3.85
$\sigma_{gg \rightarrow h}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}}$	1.27	1.31	0.45	0.40	0.65
$\sigma_{\bar{t}_1 t_1 h}^{t'} \text{ (pb) @ 7 TeV}$	0.0194	0.0760	0.0037	0.0016	$7 \cdot 10^{-4}$
$\sigma_{\bar{t}_1 t_1 h}^{t'} \text{ (pb) @ 14 TeV}$	0.138	0.539	0.036	0.021	0.015
$\sigma_{\bar{t}_2 t_2} \text{ (pb) @ 7 TeV}$	1.361	0.0936	0.0709	0.1360	0.0115
$\sigma_{\bar{t}_2 t_2} \text{ (pb) @ 14 TeV}$	13.53	1.465	1.164	1.975	0.284
$B_{t_2 \rightarrow t_1 h} \text{ (%)}$	62.6	82.1	60.8	13.5	43.0
$B_{t_2 \rightarrow t_1 Z} \text{ (%)}$	28.6	14.7	25.0	46.1	40.3
$B_{t_2 \rightarrow bW} \text{ (%)}$	8.8	3.2	14.2	40.4	16.6
$\Gamma_{t_2} \text{ (GeV)}$	4.4	3.5	19.8	6.5	8.8
$\sigma_{\bar{t}_2 t_2} B_{t_2 \rightarrow bW}^2 \text{ (pb)}$	0.01	$9 \cdot 10^{-5}$	0.001	0.022	0.000(3)
LHC bound [74]	$< 0.26$	$< 0.14$	$< 0.14$	$< 0.16$	$\times$
$\sigma_{\bar{t}_2 t_2} B_{t_2 \rightarrow t_1 Z}^2 \text{ (pb)}$	0.11	0.002	0.004	0.029	0.002
LHC bound [75]	$< 0.5$	$< 0.4$	$< 0.4$	$< 0.4$	$\times$
$S / T$	0.05 / 0.05	0.03 / 0.03	-0.01 / 0.23	-0.01 / 0.30	-0.01 / 0.28

TABLE I: Benchmark scenarios in the present  $t', t''$  model, defined by the values of the fundamental parameters, including the Higgs mass,  $m_h$ , and the resulting  $m_{t_2}$  and  $m_{t_3}$  physical masses of the heavy top-like quarks. The cross sections at NNLO,  $\sigma_{\bar{t}_2 t_2}$ , for the  $pp \rightarrow \bar{t}_2 t_2$  process, are shown at  $\sqrt{s} = 7$  TeV or 14 TeV, together with the  $t_2$  widths  $\Gamma_{t_2}$  and the  $t_2$  branching fraction values. For comparison, the SM Higgs production cross section values via gluon fusion are also given, together with the ratio  $\sigma_{gg \rightarrow h}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}}$ , between the gluon fusion cross section in the present model and in the SM. Furthermore, the NLO cross sections for Higgs production in association with a  $\bar{t}t$  pair,  $\sigma_{\bar{t}_1 t_1 h}^{t'}$ , in the present model, are shown for comparison with the  $\sigma_{\bar{t}_2 t_2}$  cross sections [the  $\sigma_{\bar{t}_1 t_1 h}^{t'}$  values are too small to contribute to the signal, analyzed in this paper, from  $\bar{t}_2 t_2$  production, with  $t_2 \rightarrow th$  decay]. Finally, the LHC upper limits and theoretical predictions for the observables  $\sigma_{\bar{t}_2 t_2} B_{t_2 \rightarrow bW}^2$ ,  $\sigma_{\bar{t}_2 t_2} B_{t_2 \rightarrow t_1 Z}^2$  are shown just above the last line (the crosses indicate the absence of experimental limit at the associated  $m_{t_2}$  values). In the last line the values of the oblique parameters  $S$  and  $T$  are given [after subtraction of the SM contributions to include only new physics effects]. For the point A1 (A2), we have used the indicated  $Y''$  value for the  $t_R''$  coupling and  $Y'' = -0.3$  ( $-1.75$ ) for the  $t_L''$  vertex.

#### IV. CONSTRAINTS FROM THE DIRECT HIGGS BOSON SEARCH

Sets **A1/A2** - At  $m_h = 125$  GeV, all the sensitive channels for searching the Higgs boson at hadron colliders are the decays  $h \rightarrow \gamma\gamma$ ,  $h \rightarrow WW$  (with  $W \rightarrow \ell\nu$ ),  $h \rightarrow ZZ$  (with  $Z \rightarrow \ell\bar{\ell}$ ),  $h \rightarrow \tau\bar{\tau}$  and  $h \rightarrow b\bar{b}$ . The latest bounds on the Higgs boson rates obtained at the LHC read as,  $\sigma_{gg \rightarrow h} B_{h \rightarrow \gamma\gamma} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \gamma\gamma}^{\text{SM}} \lesssim 2$ ,  $\sigma_{gg \rightarrow h} B_{h \rightarrow WW} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}} \lesssim 1.30$ ,  $\sigma_{gg \rightarrow h} B_{h \rightarrow ZZ} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} \lesssim 2.2$ ,  $\sigma_{gg \rightarrow h} B_{h \rightarrow \tau\tau} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \tau\tau}^{\text{SM}} \lesssim 3.2$  and  $\sigma_{gg \rightarrow h} B_{h \rightarrow b\bar{b}} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow b\bar{b}}^{\text{SM}} \lesssim 3.2$  [68–71, 77, 78]. These bounds are compatible with the rates calculated taking into account the  $t-t'-t''$  mixing effect on the top quark Yukawa coupling as well as the  $t_2$  and  $t_3$  eigenstate contributions in the triangular loop of the gluon fusion mechanism, for our parameter sets A1/A2. This parameter set yields indeed:

$$\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow \gamma\gamma}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \gamma\gamma}^{\text{SM}} = 1.16 \text{ (1.19)} \quad ; \quad \sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow WW}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}} = 1.25 \text{ (1.28)} \quad (3)$$

$$\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow ZZ}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} = 1.25 \text{ (1.28)} \quad ; \quad \sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow \tau\tau}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \tau\tau}^{\text{SM}} = 1.25 \text{ (1.28)} \quad (4)$$

$$\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow b\bar{b}}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow b\bar{b}}^{\text{SM}} = 1.25 \text{ (1.28)} \quad [A1] \text{ } ([A2]) \quad (5)$$

The cross section for the Higgs production is enhanced,

$$\sigma_{gg \rightarrow h}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} = 1.27 [A1] \text{ } (1.31 [A2]),$$

due to the combination of two possible effects: the increase of the  $t_1$  Yukawa coupling and the constructive interferences between the  $t_1$  contribution and the  $t_2, t_3$  ones. In contrast, the branching fraction for the decay channel into diphoton is slightly decreased,

$$B_{h \rightarrow \gamma\gamma}^{t'}/B_{h \rightarrow \gamma\gamma}^{\text{SM}} = 0.91 \text{ [A1]} \text{ (0.90 [A2])}.$$

But the resulting product  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow \gamma\gamma}^{t'}$  is increased relatively to the SM case as shown in Eq.(3).

Such an increased value of the observable  $\sigma_{gg \rightarrow h} B_{h \rightarrow \gamma\gamma}$ , induced here by the presence of  $t'$  quarks (*c.f.* Eq.(3)), could be indicated by the slight excess in the ATLAS [69, 70, 77, 78] and CMS [68, 71, 77] data corresponding to a possible  $\sim 125$  GeV Higgs signal in the diphoton channel. All the values of the quantities,  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow \gamma\gamma}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \gamma\gamma}^{\text{SM}}$ ,  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow WW}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}}$ ,  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow ZZ}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}}$ ,  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow \tau\tau}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow \tau\tau}^{\text{SM}}$  and  $\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow b\bar{b}}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow b\bar{b}}^{\text{SM}}$ , in Eq.(3)-(5), are also compatible with the CMS and ATLAS best-fit values whose central value, from the combination of all search channels, is of  $1.22^{+0.31}_{-0.39}$  [71] (for a Higgs mass hypothesis of 124 GeV) [106] and  $0.90^{+0.40}_{-0.37}$  [78] (for a Higgs mass hypothesis of 126 GeV), respectively [107].

It is also interesting to note that the present theoretical model allows for either an increase of  $\sigma_{gg \rightarrow h}^{t'}$  compared to the SM, as here for A1/A2, or a decrease as with the parameter sets in the following.

Sets **B,C** - For these sets of parameters where  $m_h = 255$  GeV or 320 GeV, all the Higgs decays have negligible widths relatively to the dominant channels  $h \rightarrow ZZ$  and  $h \rightarrow WW$ , as in the SM case. Hence the branching fractions  $B_{h \rightarrow ZZ}$  and  $B_{h \rightarrow WW}$  remain unchanged in the present model with vector-like top quarks where only the decay widths for  $h \rightarrow t\bar{t}$ ,  $h \rightarrow gg$ ,  $h \rightarrow \gamma\gamma$  and  $h \rightarrow \gamma Z$  are modified. In consequence, the experimental limits on  $\sigma_{gg \rightarrow h}/\sigma_{gg \rightarrow h}^{\text{SM}} \lesssim 0.45$  (0.40) [for  $m_h \simeq 255$  (320) GeV] issued from the LHC combined investigations using the  $h \rightarrow ZZ, WW$  channels exclusively [68–71, 77, 78] can be applied directly to our framework where one gets

$$\sigma_{gg \rightarrow h}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} = 0.45 \text{ [B]} ; 0.40 \text{ [C]} \quad (6)$$

which does not conflict with the above LHC limits.

Note that for the point C,  $\sigma_{gg \rightarrow h}^{t'}$  is strongly reduced compared to SM. A factor 1/10 could even be achieved in the present theoretical model but variants of the multiplet choice (non-minimal in term of field content), allowing coupling correction cancellations, should then be used instead to pass the indirect constraints discussed in Section V.

Set **D** - For  $m_h = 540$  GeV, the Higgs boson is searched only through its decays into  $ZZ$  and  $WW$ . The strongest bounds on the Higgs rates from the LHC read as  $\sigma_{gg \rightarrow h} B_{h \rightarrow ZZ}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} \lesssim 0.90$  and  $\sigma_{gg \rightarrow h} B_{h \rightarrow WW}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}} \lesssim 1.45$  [68–71, 77, 78]. These upper limits are clearly in good agreement with the rates calculated in the presence of the  $t'$  and  $t''$  states (that modifies  $B_{h \rightarrow t\bar{t}}$ ) for the set D, namely,

$$\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow ZZ}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} = 0.69 \quad \sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow WW}^{t'}/\sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}} = 0.69 \quad (7)$$

where

$$B_{h \rightarrow ZZ}^{t'}/B_{h \rightarrow ZZ}^{\text{SM}} = 1.06 \quad B_{h \rightarrow WW}^{t'}/B_{h \rightarrow WW}^{\text{SM}} = 1.06 \text{ [D]}.$$

## V. THE INDIRECT CONSTRAINTS AND OBLIQUE PARAMETERS

Given the absence of precise measurement for the  $Zt\bar{t}$  vertex (coupling directly modified by the  $t - t' - t''$  mixing), the main indirect constraints to the present model come from the corrections to the gauge boson vacuum polarizations induced by the loops of  $q_{5/3}, t', t''$  states. The values of the oblique parameters  $S, T$  that we obtain, according to the preliminary calculations of Ref. [79, 80], are given in Table I. They appear to belong to the  $1\sigma$  regions induced by the long list of EW precision observables measured mainly at the LEP collider [81].

Remark that the input parameters of Table I (i.e. the theoretical values in the first four lines) have been chosen to fix a panel of characteristic benchmark points for  $m_{t_2}$  that pass the indirect constraints as well as the bounds from direct Higgs search described in previous section; however those two types of constraints allow large domains of the parameter space (varying also  $m_h$ ). The precise setting of the  $Y$  coupling reflects mainly the experimental precision on the top quark mass measurement (and not any fine-tuning).

The  $t', t''$  states could contribute to Flavor Changing Neutral Current (FCNC) reactions which are experimentally well constrained; from the theoretical point of view, these FCNC contributions rely precisely on the whole set of Yukawa coupling constants for the entire quark sector. The treatment of such an high degree of freedom in the parameter space is beyond the scope of the present study.

Finally, given the relative heaviness of the  $t_2$  quark, we have checked that the predicted value for the  $V_{tb}$  CKM matrix element is in agreement with the experimental measurement close to unity obtained (without assuming  $3 \times 3$  unitarity) through the single top quark production cross section at Tevatron [81].

## VI. HIGGS SIGNAL RECONSTRUCTION IN $\bar{t}_2 t_2 \rightarrow th + X$ EVENTS

We have studied the sensitivity at the LHC with  $\sqrt{s} = 14$  TeV of a search for  $pp \rightarrow t_2 \bar{t}_2$  production, with one of the  $t_2$  decaying to  $th$ , and the other decaying to  $bW$  or  $tZ$  or  $th$ , resulting into  $thbW$ ,  $thtZ$  and  $thth$  final states, respectively. For a best sensitivity and in order to measure the Higgs mass precisely, we have exploited the Higgs decay channel into  $ZZ$  to four charged leptons for the signals with Higgs mass above 200 GeV (points B, C, D) while the Higgs decay into two photons is considered for the signals with a Higgs mass of 125 GeV (sets A1 and A2).

For the signal event generation, we have implemented the couplings of our  $t_2$  model in **FeynRules** [82] [108] interfaced with **MadGRAPH** [83] for the *Monte Carlo* generation, **PYTHIA** [84] for the hadronization part and **DELPHES** [85] for the fast simulation of a typical LHC detector response. Signal events are generated for the  $t_2$  and  $h$  masses corresponding to the parameter sets described in Table I, for the three final states  $thbW$ ,  $thtZ$  and  $thth$ . Events corresponding to points A1 and A2 are generated with the Higgs decaying through  $h \rightarrow \gamma\gamma$ , while for points B, C and D the  $h \rightarrow ZZ$  decay is retained for the sensitivity studies described in this Section. The main backgrounds were generated with **ALPGEN** [86] interfaced to **PYTHIA** and **DELPHES**, as for the signal events. Physics objects used for the analysis (photons, leptons and jets) were defined emulating the requirements used in real CMS Higgs searches in the 2011 data. In particular, we followed closely the physics object definition as for the real data 7 TeV Higgs analysis in the diphoton channel [87] and in the four lepton channel [88].

In the following the quoted number of events and distributions are normalized to an integrated luminosity of 20 fb $^{-1}$  multiplied by, for the different signal final states, their expected  $\sigma_{\bar{t}_2 t_2}$  cross section times branching fractions (hereafter referred to as signal event yield per unit of integrated luminosity), while, for background processes, their **ALPGEN** cross sections are used. The signal event yield in the different final states depends upon the parameter set under consideration. In Table II, we summarize, for each parameter set described in Table I, the physical signal  $m_{t_2}$  and  $m_h$  masses, the  $\sigma_{\bar{t}_2 t_2}$  cross sections, the  $t_2$  branching fractions into  $bW$  ( $B_{t_2 \rightarrow bW}$ ),  $tZ$  ( $B_{t_2 \rightarrow tZ}$ ),  $th$  ( $B_{t_2 \rightarrow th}$ ) final states, as well as the  $h$  branching fractions into  $\gamma\gamma$  (for sets A1 and A2) and into  $ZZ$  (for sets B, C and D), reporting the expected SM branching fraction values and the factor  $f_{h \rightarrow VV}^{t'/SM}$  (see Section IV) by which it is modified in the present model. The last three columns of Table II show the expected signal event yield, for  $thbW$ ,  $thtZ$  and  $thth$  final states, with one Higgs boson decaying via to diphoton or  $ZZ$  final state. They are calculated as follows:

$$\begin{aligned} thbW \text{ final state, } Y_S(h \rightarrow VV) &= 2 B_{t_2 \rightarrow th} B_{t_2 \rightarrow bW} B_{h \rightarrow VV}^{SM} f_{h \rightarrow VV}^{t'/SM} \sigma_{\bar{t}_2 t_2} \\ thtZ \text{ final state, } Y_S(h \rightarrow VV) &= 2 B_{t_2 \rightarrow th} B_{t_2 \rightarrow tZ} B_{h \rightarrow VV}^{SM} f_{h \rightarrow VV}^{t'/SM} \sigma_{\bar{t}_2 t_2} \\ thth \text{ final state, } Y_S(h \rightarrow VV) &= 2 B_{t_2 \rightarrow th}^2 B_{h \rightarrow VV}^{SM} f_{h \rightarrow VV}^{t'/SM} \sigma_{\bar{t}_2 t_2} \end{aligned}$$

For  $thth$  events, the event yield is given for events where one  $h$  decays to vector bosons, while the second  $h$  decays inclusively. The signal event yield (in fb) multiplied by the integrated luminosity (in fb $^{-1}$ ) results into the numbers of produced signal events for that luminosity. We note that, for a chosen Higgs decay, the signal yield depends on both  $\sigma_{\bar{t}_2 t_2}$  and  $B_{t_2 \rightarrow th}$ . Then, for example, in spite of the fact that  $\sigma_{\bar{t}_2 t_2}$  is larger for point C than B, the signal event yield is higher for point B than C, because of the larger  $B_{t_2 \rightarrow th}$  value in point B. The background cross sections are listed in Table III, for the four lepton search channel, and in Table IV for the diphoton search channel.

Parameter set	$m_{t_2}$ (GeV)	$m_h$ (GeV)	$\sigma_{\bar{t}_2 t_2}$ (fb)	$B_{t_2 \rightarrow th}$	$B_{t_2 \rightarrow tZ}$	$B_{t_2 \rightarrow bW}$	$B_{h \rightarrow VV}^{SM}$	$f_{h \rightarrow VV}^{t'/SM}$	$Y_S(h \rightarrow VV)$ (fb)		
									$thbW$	$thtZ$	$thth$
Point A1	403	125	$1.353 \cdot 10^4$	0.626	0.286	0.088	$2.29 \cdot 10^{-3}$	0.91	3.11	10.1	22.1
Point A2	599	125	$1.465 \cdot 10^3$	0.821	0.147	0.032	$2.29 \cdot 10^{-3}$	0.90	0.159	0.729	4.07
Point B	626	255	$1.164 \cdot 10^3$	0.608	0.250	0.142	0.298	1.00	59.9	105	256
Point C	572	320	$1.975 \cdot 10^3$	0.135	0.461	0.404	0.309	1.00	66.6	76.0	22.2
Point D	788	540	$0.284 \cdot 10^3$	0.430	0.403	0.166	0.265	1.06	11.4	27.6	29.5

TABLE II: Information entering the signal event yield  $Y_S$  calculation. The  $t_2$  pair production cross section at 14 TeV and  $t_2$  branching fraction values are from Table I. The ratio  $f_{h \rightarrow VV}^{t'/SM} = B_{h \rightarrow VV}^{t'}/B_{h \rightarrow VV}^{SM}$  values are calculated in Section IV. The event yield  $Y_S$ , per unit of integrated luminosity, is given for the different final states  $\bar{t}_2 t_2 \rightarrow thbW$ ,  $thtZ$ ,  $thth$  and  $h \rightarrow \gamma\gamma$ , for points A1 and A2, or  $h \rightarrow ZZ$ , for points B, C, D. For  $thth$  events, the event yield is calculated for the case where one  $h$  decays to vector bosons, while the second  $h$  decays inclusively. This synoptic table summarizes at once, for convenience, all the relevant numbers useful for the experimental search.

### A. Search for $\bar{t}_2 t_2 \rightarrow th + X$ signal in the four leptons plus multijets channel

In order to estimate the sensitivity of a search for  $thbW$ ,  $thtZ$  and  $thth$  final states, when the Higgs boson is relatively heavy, as expected for the points B, C and D, with  $m_h = 255, 320, 540$  GeV, respectively, we exploit the decay channel into four charged leptons  $h \rightarrow ZZ \rightarrow 4l$ . Signals from  $thbW$ ,  $thtZ$ ,  $thth$ ,  $h \rightarrow ZZ \rightarrow 4l$ , final states

are characterized by four high transverse momentum leptons, from the Higgs decay, and a large number of energetic jets, from accompanying top and heavy vector boson decays.

The event selection, exploiting the large number of high transverse momentum ( $p_T$ ) leptons and jets, as well as the b-jet content of the event, consists of the following criteria:

- Four leptons (muons or electrons) are required with transverse momentum  $p_T > 20$  GeV and pseudo-rapidity  $|\eta| < 2.4$  or 2.5 for muons or electrons, respectively, and two lepton pairs, each pair with same flavor but opposite charge leptons. The lepton pair of highest  $p_T$  is required to have a dilepton invariant mass consistent with the Z mass,  $M_{2l} = M_Z \pm 15$  GeV, while the lepton pair with second highest dilepton  $p_T$  must have a dilepton invariant mass  $M_{2l} > 12$  GeV;
- $H_T > 1000$  GeV and  $N_j > 5$ , with  $H_T$  being defined as the scalar sum of the transverse momenta of identified leptons, photons, jets, and the missing energy, and  $N_j$  being the number of hadronic jets with  $p_T > 30$  GeV and  $|\eta| < 2.4$ ;
- At least two b-tagged jets in the event.

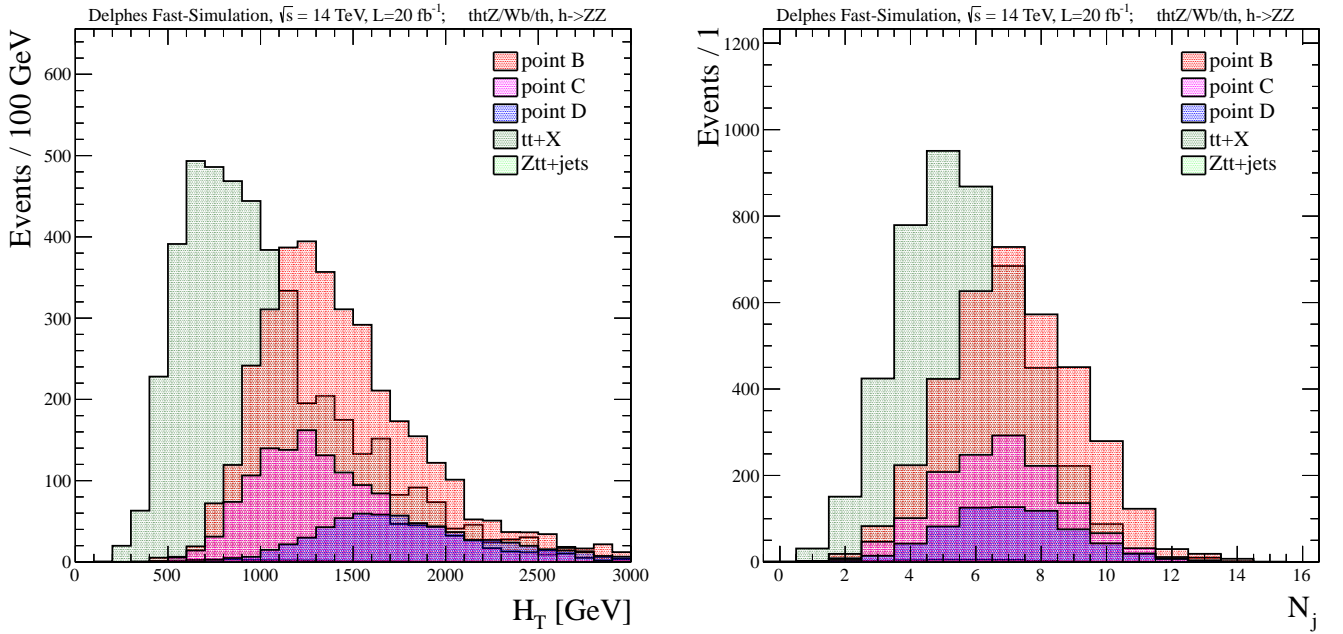


FIG. 1: Distributions of the  $H_T$  variable and the jet multiplicity  $N_j$  after four lepton requirements. Background and signal distributions are shown overlaid, to compare the different distribution shapes, with the background normalized to the expected events for  $20 \text{ fb}^{-1}$  and the corresponding signal expectation multiplied by a factor of fifty.

The motivation for the  $H_T$  and  $N_j$  cuts is evident from Figure 1, showing the  $H_T$  and  $N_j$  distributions after the four lepton requirements. The event numbers are shown for an integrated luminosity  $L = 20 \text{ fb}^{-1}$ , with the signal event numbers multiplied by a factor of fifty, for shape comparison. Expectations for the signals, by final state, and the background processes, after the selection cuts, for an integrated luminosity of  $L = 20 \text{ fb}^{-1}$ , are shown in Table III, where the following quantities are reported:

- $Y_S$ , the signal event number produced, per unit of integrated luminosity, given for each signal parameter set and final state under study, as reported in Table II;
- $\sigma$ , the cross sections, as calculated by the ALPGEN generator, for the background processes included in the present study;
- $N_{4l}$ , the number of events after four lepton requirements;
- $N_{N_j, H_T}$ , the number of events after the additional requirements  $H_T > 1000$  GeV and  $N_j > 5$ ;
- $N_{2b}$ , the number of events after the additional requirements of two b-tagged jets in the event;

- $S$  and  $B$ , the total number of signal (summed over all signal final states) and background (summed over all background processes), after a cut on the reconstructed four lepton invariant mass,  $M_{4l}$ , with  $\Delta B$  being the expected uncertainty on the total number of background events. Here we only consider the statistical uncertainty  $\Delta B = \sqrt{B}$ , but a more realistic estimation should also include systematic uncertainties on the number of background events. Some of the dominant systematic uncertainties are depending on detector effects (for instance jet energy resolution) and can be best evaluated with real data. In the following, an estimation of the signal sensitivity is given as the ratio  $S/\Delta B$ , measuring the signal in terms of background standard deviations.

Signal: $thbW/thtZ/thth, h \rightarrow ZZ$					Total signal $S, M_{4l}(\text{GeV})$ cut			
Parameter set	$Y_S$ (fb)	$N_{4l}$	$N_{N_j, H_T}$	$N_{2b}$	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
Point B	59.9 /105 /256	8.1 /23.7 /37.8	5.5 /18.0 /28.9	3.52 /11.5 /18.5	33.4	30.4	17.0	4.9
Point C	66.6 /76.0 /22.2	7.7 /15.8 /3.1	4.8 /11.3 /2.2	3.07 /7.23 /1.41	11.7	10.7	7.4	2.0
Point D	11.4 /27.6 /29.5	1.5 /6.6 /4.7	1.1 /5.3 /3.9	0.70 /3.40 /2.50	6.6	6.2	5.1	2.7
Background					Total background $B, M_{4l}(\text{GeV})$ cut			
Process	$\sigma(\text{fb})$	$N_{4l}$	$N_{N_j, H_T}$	$N_{2b}$	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
$t\bar{t}$ + jets	$9.19 \cdot 10^5$	4680	1480	27.5	35.5	23.5	13.2	6.8
$t\bar{t}b\bar{b}$ + jets	$2.50 \cdot 10^3$	5.60	3.10	2.0	Statistical $\Delta B, M_{4l}(\text{GeV})$ cut			
$t\bar{t}W$ + jets	$1.99 \cdot 10^2$	1.20	0.40	0.036	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
$t\bar{t}Z$ + jets	97.3	25.0	9.5	6.0	6.0	4.9	3.6	2.6

TABLE III: Cross section and number of expected events after different selection cuts (see text), for an integrated luminosity of  $20 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}$ , in the search for  $thbW, thtZ$  and  $thth$  final states, with  $h \rightarrow ZZ$ , in the four leptons plus multijets channel. The number of events is given separately for each signal final state ( $thbW/thtZ/thth$ ) and for each background process. In the four rightmost columns,  $S$ , the total number of signal events (summed over all signal final states), and  $B$ , the total number of background events (summed over all background processes), are given after all selection cuts but the  $M_{4l}$  cut, in column “no  $M_{4l}$  cut”, and after three different  $M_{4l}$  cut values. The  $S$  values for points B, C and D are given on the same lines as indicated in column “Parameter set”. The  $B$  values in the column “no  $M_{4l}$  cut” are the sum of the individual background contributions as reported in the background column under “ $N_{2b}$ ”. The quantity  $\Delta B = \sqrt{B}$  is the expected statistical uncertainty on the total number of background events. In the text, the signal sensitivity is given as the ratio  $S/\Delta B$ .

The need for additional cuts, after the leptons, jets and  $H_T$  requirements, is seen in Table III, where the  $N_{N_j, H_T}$  column shows that after these cuts, a large background, predominantly from  $t\bar{t}$  + jets production, is still present. Further background rejection can be obtained with requirements on the number of b-tagged jets. The motivation is the following: in  $t\bar{t}$  events the requirement of four high  $p_T$  leptons strongly reduces the number of b-taggable jets. Indeed, in  $t\bar{t}$ +jets events, while two high  $p_T$  leptons are provided by the two leptonic W decay, the additional two leptons are preferentially resulting from the two  $b$  decays. Thus, applying a  $b$ -tagging requirement can reduce significantly the  $t\bar{t}$  contribution. In the signal case, the four leptons come mainly from the  $h \rightarrow ZZ \rightarrow 4l$  decay so that there are in average at least two  $b$ -taggable jets in the event, for which a  $b$ -tagging requirement can have high efficiency. Since no detailed b-tagging information is presently available in DELPHES, we make use of known  $b$ -tagging and mis-tagging efficiency values as measured by LHC experiments (see *e.g.* Ref. [89]), to estimate the effect on background and signal of requiring two b-tagged jets in the event. The probability for a  $b$ -jet to be b-tagged is taken to be  $\epsilon_{b\text{-tag}} = 0.8$  and for a mis-tagging the probability is  $\epsilon_{\text{mis-tag}} = 0.05$ . An event-by-event weight, that is an estimation of the probability that two  $b$ -jets be identified in the event, is applied to both background and signal events. The number of expected events, for signals and backgrounds, resulting from leptons, jets and b-tagging requirement are shown in the column  $N_{2b}$  of Table III.

The corresponding distributions of the invariant mass of the four leptons,  $M_{4l}$ , for signals and backgrounds are shown in Figure 2. The mass peak corresponding to the generated Higgs mass is reconstructed at the correct mass value with good resolution ( $\Delta M_{4l}/M_{4l} \lesssim 10\%$ ). Signal events, with reconstructed mass significantly lower, or higher, than the generated Higgs mass value, are in general events where one lepton from the  $h \rightarrow ZZ \rightarrow 4l$  decay does not pass the lepton selection criteria, while another lepton from an accompanying  $W$  or  $Z$  decays is selected to reconstruct the four lepton invariant mass. The background, mainly from the  $t\bar{t}$  + jets process, is mostly concentrated in the  $M_{4l}$  region below 200 GeV. Applying a lower cut on  $M_{4l}$  removes a large fraction of the background and improves the signal significance, as shown in Table III.

An additional distribution of the variable,  $M_{4l3j}$ , is shown after all but the  $M_{4l}$  cuts. This variable can help estimating directly the mass of the heavy top-like quark. It is defined as the invariant mass of the system obtained by associating to the four lepton momentum direction the three closest jets (expected to come from the decay of the accompanying top-quark,  $t \rightarrow bW$ ,  $W \rightarrow 2 \text{ jets}$ ), choosing among all the jets in the event those with the smallest  $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$  with respect to the four lepton momentum direction. The distributions of  $M_{4l3j}$  for signals and backgrounds are shown in Figure 2. A broad peak, whose width is dominated by the jet energy resolution and jet combinatorics, is observed centered at about the generated  $t_2$  mass value (the  $t_2$  physical width is given in Table I) for the points B and C having larger  $t_2$  pair production rates than for the set D. Therefore, this mass reconstruction



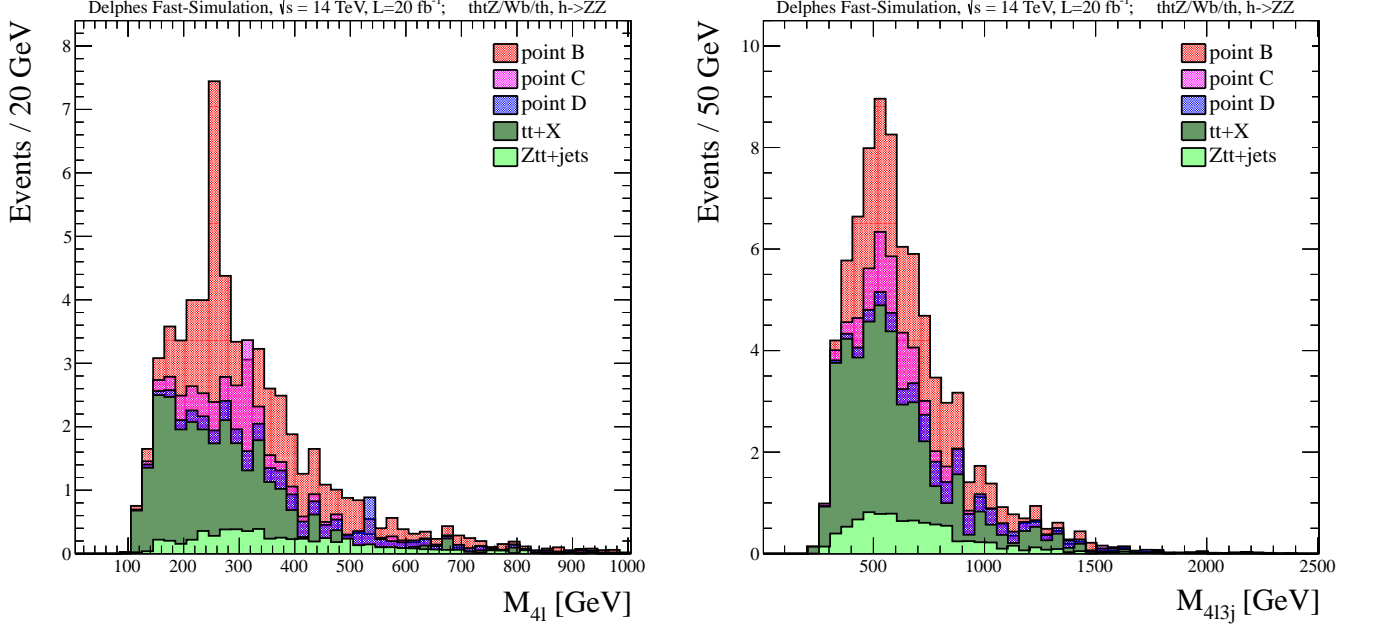


FIG. 2: Distributions of the four lepton invariant mass,  $M_{4l}$ , and of the reconstructed heavy top-partner mass,  $M_{4l3j}$  (see text), after all selection cuts. Signal and background distributions, normalized to the expected events for  $20 \text{ fb}^{-1}$ , are shown stacked to indicate their relative contributions. Signal distributions for points B, C and D correspond to Higgs mass  $m_h = 255$ , 320 and 540 GeV, respectively.

method, together with the four lepton mass reconstruction, will give an early indication that a heavy particle has been produced in the collision and decayed into a Higgs boson (identified by the four lepton mass peak) plus three jets. Another mass reconstruction method, described in the next section, that exploits the property of the two heavy particles having equal mass, will give another characterization of the origin of the observed signal. Ultimately, a kinematic fit technique (utilized, for instance, in top quark mass measurements, see e.g. [90]), to test on an event-by-event basis the hypothesis that the event results from the production of two heavy particles of equal mass (see e.g. [91]) – one of which decays into two particles with known decays and masses (three jets, with invariant mass around the top mass, and four leptons, with invariant mass around the value measured from the four lepton mass peak, see Figure 2) – can be properly applied in real data events, when the detailed parameterizations of the experimental resolutions of the physics objects entering the fit can be obtained from data.

The numbers of signal and background events expected after all cuts, and for  $M_{4l} > 200$ , 300 and 500 GeV, are shown in the three rightmost columns of Table III together with the expected statistical background standard deviation  $\Delta B$  for the three signal points investigated in this search channel. We estimate that, for an integrated luminosity of  $20 \text{ fb}^{-1}$ , a signal corresponding to point B is detectable with a significance  $S/\Delta B \sim 6$  (after  $M_{4l} > 200$  GeV cut). For this benchmark point the  $B_{t_2 \rightarrow th}$  branching fraction is  $\sim 0.6$ . Then, for similar  $t_2$  cross section,  $t_2$  mass and  $h$  mass values, a signal could be discovered, with  $S/\Delta B \gtrsim 5$ , for  $B_{t_2 \rightarrow th} \gtrsim 0.5$ . For point C, with  $B_{t_2 \rightarrow th} \sim 0.1$  we obtain a signal significance  $S/\Delta B \sim 2$ . A signal significance of five and above is then obtained for  $B_{t_2 \rightarrow th} \gtrsim 0.25$ . For smaller  $B_{t_2 \rightarrow th}$  values, a larger integrated luminosity, or a more optimal analysis, would be needed for a signal significance of five or above. For point D, with  $B_{t_2 \rightarrow th} \sim 0.4$ , we obtain a signal significance  $S/\Delta B \sim 1.4$  thus even for maximal  $B_{t_2 \rightarrow th} \sim 1$  a signal significance of  $\sim 3.5$  is attainable. Higher integrated luminosity, or higher background rejection, depending on the  $B_{t_2 \rightarrow th}$  value (for  $B_{t_2 \rightarrow th} \sim 0.4$ , about a factor of ten larger luminosity or background rejection) is needed for a five sigma signal significance corresponding to the D scenario, with a  $t_2$  mass of about 800 GeV and a pair production cross section of about 0.3 pb.

### B. Search for $\bar{t}_2 t_2 \rightarrow th + X$ signal in the diphoton plus multijets channel

To study the sensitivity of a search for  $thtZ$ ,  $thbW$  and  $thth$  final states, when the Higgs boson is relatively light, as for points A1 and A2, with  $m_h = 125$  GeV, we exploit the  $h \rightarrow \gamma\gamma$  decay channel. As for a light Higgs boson in the SM, in spite of the relatively small expected  $B(h \rightarrow \gamma\gamma)$  value, this is expected to be a channel with good signal sensitivity, due to the good diphoton mass resolution, allowing to identify the Higgs mass signal over a background that can be well measured in the side-bands.

The background processes considered in this study are listed in Table IV. To reduce generation time for the

background events, we have applied cuts on **ALPGEN** generated parton quantities, that are looser than the cuts applied on the reconstructed physics objects. The generator level cuts are: photon  $p_T > 20$  GeV and  $|\eta| < 3.0$ , jet  $p_T > 20$  GeV and  $|\eta| < 2.5$ ,  $\Delta R_{\gamma j} < 0.4$ ,  $\Delta R_{\gamma l} < 0.4$ ,  $\Delta R_{jj} < 0.4$  and  $\Delta R_{t\bar{t}} < 0.4$ . Background cross sections for these generator level cuts as calculated by **ALPGEN** are listed in Table IV. An additional background is the  $\gamma\gamma$ +jets process. A relatively large inclusive diphoton cross section is expected [92] and is going to be measured at the LHC, together with the contribution from fake diphoton pairs. The inclusive diphoton cross section in the diphoton mass region of interest can be large (order of pb), but we expect that the large jet multiplicity requirement scales down this contribution by at least three orders of magnitude, thus reducing its cross section to few fb. An additional handle to minimize this background will be the b-tagging, that can reduce the contribution from light flavored multi-jets events by two or three order of magnitudes (as discussed in the previous section), while retaining a large fraction of the signal events containing at least two b-jets. However, b-tagging will not effectively reduce backgrounds with t-quark pairs in the final state, as in the case of  $t\bar{t}\gamma\gamma$  + jets process. Thus, conservatively we have not exploited b-tagging for this analysis of the  $h \rightarrow \gamma\gamma$  channel.

Signals from  $thbW$ ,  $thtZ$ ,  $thth$ ,  $h \rightarrow \gamma\gamma$ , final states are characterized by a large number of energetic jets, from top and heavy vector boson decays, in addition to the two high transverse momentum photons from the Higgs decay. The event selection consists of the following criteria:

- Photons are required to be within  $|\eta| < 2.5$  and isolated. The isolation requirements imply that, within a cone  $\Delta R = 0.4$  around the photon direction, the charged particle energy measured in the tracker is  $< 2.0$  GeV, the electromagnetic calorimeter (ecal) energy in the cone is  $< 4.2$  GeV, the hadronic calorimeter (hcal) energy in the cone is  $< 2.2$  GeV and the ratio between the ecal and hcal energy in the cone is  $< 0.05$ . Two isolated photons are required, with the leading photon  $p_T > 45$  GeV and the second photon  $p_T > 30$  GeV. The invariant mass of the two photon is required to be  $M_{2\gamma} > 90$  GeV.
- Hadronic jets are counted if they have  $p_T > 30$  GeV and  $|\eta| < 2.4$ . Events are required to have a number of jets  $N_j > 6$ , at preselection, or  $N_j > 8$ , for the final selection, after which the signal sensitivity is evaluated in a sliding window in the diphoton invariant mass  $M_{2\gamma}$ .

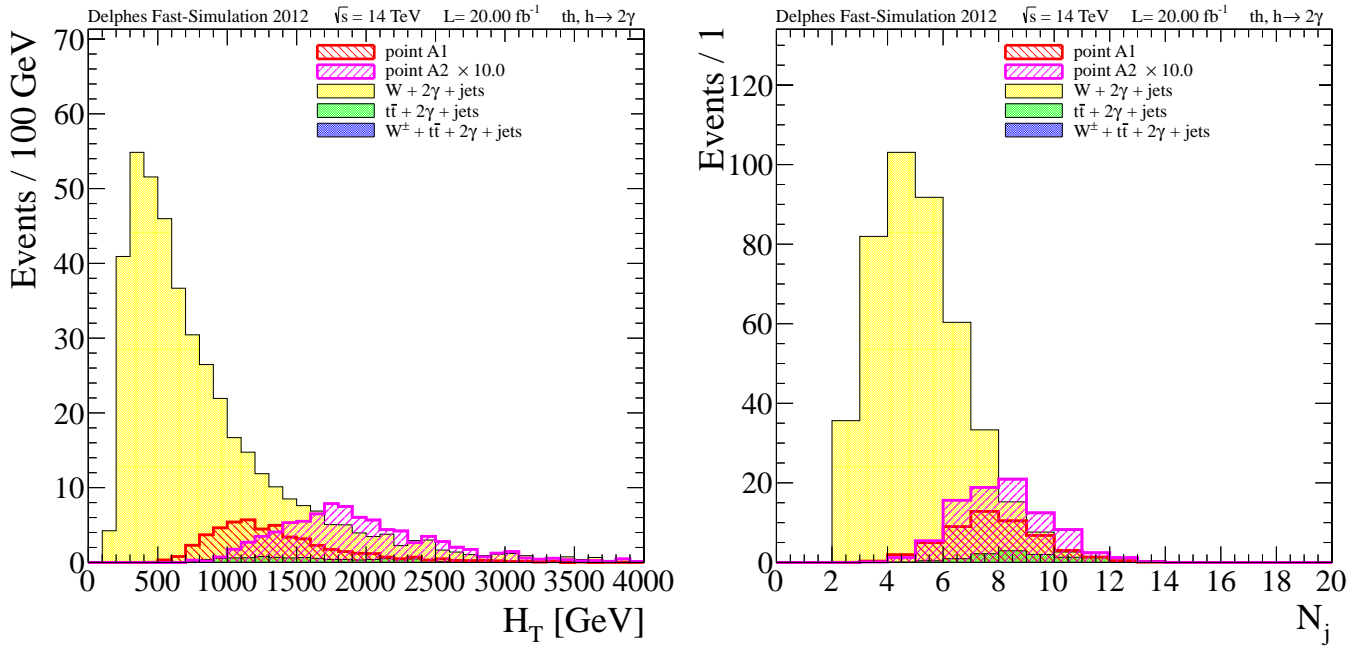


FIG. 3: Distributions of the  $H_T$  variable and the jet multiplicity  $N_j$  after diphoton requirements, including a diphoton invariant mass cut  $M_{2\gamma} > 90$  GeV.

Figure 3 shows the  $H_T$  and  $N_j$  distributions after the after diphoton requirements, including a diphoton invariant mass cut  $M_{2\gamma} > 90$  GeV. The distributions are shown for an integrated luminosity  $L = 20 \text{ fb}^{-1}$ , with the signal expectation for point A2 multiplied by a factor of ten, for shape comparison. Because of the relatively light  $t_2$  mass in point A1, an  $H_T > 1000$  GeV cut, as applied for points B, C and D, would reject a significant fraction of this signal. A lower  $H_T$  cut would not improve significantly the signal-over-background ratio after the  $N_j$  requirement, thus no  $H_T$  cut is applied in this channel. Expectations for the signals, by final state, and the background processes, after the selection cuts, for an integrated luminosity of  $L = 20 \text{ fb}^{-1}$ , are shown in Table IV, where the following quantities are reported:

- $Y_S$ , the signal event number produced, per unit of integrated luminosity, given for each signal parameter set and final state under study, as reported in Table II;
- $\sigma$ , the background cross sections, as calculated from the ALPGEN generator, for the background processes included in the present study;
- $N_{2\gamma}$ , the number of events after diphoton and  $M_{2\gamma} > 90$  GeV requirements;
- $N_{N_j > 6}$  and  $N_{N_j > 8}$  the number of events after the additional jet multiplicity cuts;
- $S$  and  $B$ , the total number of signal (summed over all signal final states) and background (summed over all background processes), after a cut  $M_{2\gamma}$ , with  $\Delta B$  being the expected statistical uncertainty (standard deviation) on the total number of background events. An estimation of the expected signal sensitivity can then be evaluated as the ratio  $S/\Delta B$ , measuring the signal in terms of background standard deviations.

Parameter set	Signal: $thbW/thtZ/thth, h \rightarrow \gamma\gamma$				Total signal $S, M_{2\gamma}(\text{GeV})$ cut	
	$Y_S$ (fb)	$N_{2\gamma}$	$N_{N_j > 6}$	$N_{N_j > 8}$	$M_{2\gamma} > 90$	$M_{2\gamma} \in [115, 135]$
Point A1	3.1 / 10.1 / 22.1	5.4 / 15.4 / 30.4	4.1 / 12.7 / 27.1	1.4 / 6.2 / 14.5	22.1	17.7
Point A2	0.16 / 0.73 / 4.1	0.34 / 1.35 / 6.98	0.27 / 1.17 / 6.6	0.10 / 0.62 / 3.8	4.5	3.2
Process	Background				Total background $B, M_{2\gamma}(\text{GeV})$ cut	
	$\sigma(\text{fb})$	$N_{M_{2\gamma} > 90}$	$N_{N_j > 6}$	$N_{N_j > 8}$	$M_{2\gamma} > 90$	$M_{2\gamma} \in [115, 135]$
$W\gamma\gamma + \text{jets}$	450	422	110	19.6	27.8	4.38
$t\bar{t}\gamma\gamma + \text{jets}$	15.5	11.8	11.3	8.18	Statistical $\Delta B, M_{2\gamma}(\text{GeV})$ cut	
$t\bar{t}W\gamma\gamma + \text{jets}$	0.0678	0.0577	0.0515	0.0272	$M_{2\gamma} > 90$	$M_{2\gamma} \in [115, 135]$
					5.3	2.1

TABLE IV: Cross section and number of expected events after different selection cuts (see text), for an integrated luminosity of  $20 \text{ fb}^{-1}$  at  $\sqrt{s} = 14 \text{ TeV}$ , in the search for  $thbW, thtZ$  and  $thth$  final states, with  $h \rightarrow \gamma\gamma$ , in the diphoton plus multijets channel. The number of events is given separately for each signal final state ( $thbW/thtZ/thth$ ) and for each background process. In the two rightmost columns,  $S$ , the total number of signal events (summed over all signal final states), and  $B$ , the total number of background events (summed over all background processes), are given after all selection cuts in column “ $M_{2\gamma} > 90$ ” and within a mass window  $M_{2\gamma} \in [115, 135] \text{ GeV}$  in the next column. The  $S$  values for points A1 and A2 are given in the same lines as indicated in column “Parameter set”. The  $B$  values in the column “ $M_{2\gamma} > 90$ ” are the sum of the individual background contributions as reported in the background column under “ $N_{N_j > 8}$ ”. The quantity  $\Delta B = \sqrt{B}$  is the expected statistical uncertainty on the total number of background events. In the text, the signal sensitivity is given as the ratio  $S/\Delta B$ .

In virtue of the good diphoton mass resolution ( $\sim 1\%$  to  $5\%$  for a 110 to 130 GeV Higgs boson, depending on photon selection criteria) of the detector, a highly discriminating quantity after selection is the reconstructed diphoton mass. The diphoton invariant mass distribution for signals and backgrounds events, after the  $N_j > 8$  requirement, is shown in Figure 4. Also shown is the distribution of an additional variable,  $M_{re\ n_j}$ , that could help estimating the mass of the heavy top-like quark. This is defined as the invariant mass of the system of  $n$  jets recoiling against the diphoton+ $m$  jets system, where the  $m$  jets are the closest in  $\Delta R$  to the diphoton direction. The recoiling  $n$  jets, with  $n = N_j - m$ , are counted to minimize, among all  $m$  and  $n$  choices in the event, the difference between the mass of the diphoton+ $m$  jets system and the mass of the recoiling  $n$  jets. The goal of this procedure is to separate the event into two hemispheres, one identified by the diphoton+ $m$  jets system and the other by the recoiling  $n$  jets, with  $m$  and  $n$  chosen in such a way that the invariant masses of the physics objects in the two hemispheres are about the same (within resolution), as in the case of two heavy particles decaying in diphoton plus jets, in one hemisphere, and into jets, in the other hemisphere.

On the distributions of  $M_{re\ n_j}$  for signals and backgrounds, after all but the  $M_{2\gamma}$  window cut, shown in Figure 4, a broad peak, whose width is dominated by the jet energy resolution, is observed centered at about the generated  $t_2$  masses. Hence, this mass reconstruction method will provide an early indication that two heavy particles of equal mass have been produced in the event and a first estimation of the  $t_2$  mass. In real data, where the detailed measurements of the experimental resolutions are available, kinematic fits can be applied to test the pair production and decay hypothesis and possibly to reduce the uncertainty on the  $t_2$  mass estimation.

The total number of signal and background events, after diphoton and jet multiplicity requirements, with a diphoton mass in the window between 115 GeV and 135 GeV, is also given in Table IV. We estimate that for an integrated luminosity of  $20 \text{ fb}^{-1}$ , a signal, corresponding to the benchmark point A1, is detectable with a significance  $S/\Delta B \sim 9$ . For this benchmark point the  $B_{t_2 \rightarrow th} \sim 0.6$ . Then, for a similar  $t_2$  cross section and  $t_2, h$  mass values, a signal could still be discovered, with a signal significance of about or above five, if  $B_{t_2 \rightarrow th} \gtrsim 0.3$ . For point A2, where the  $\sigma_{t_2 t_2}$  is about an order of magnitude lower than in point A1, while  $B_{t_2 \rightarrow th} \sim 0.8$ , the expected signal significance is  $\sim 1.5$ . Then, to reach a signal significance of five, at least a factor of ten larger luminosity, or a better background rejection, is needed to observe this signal.

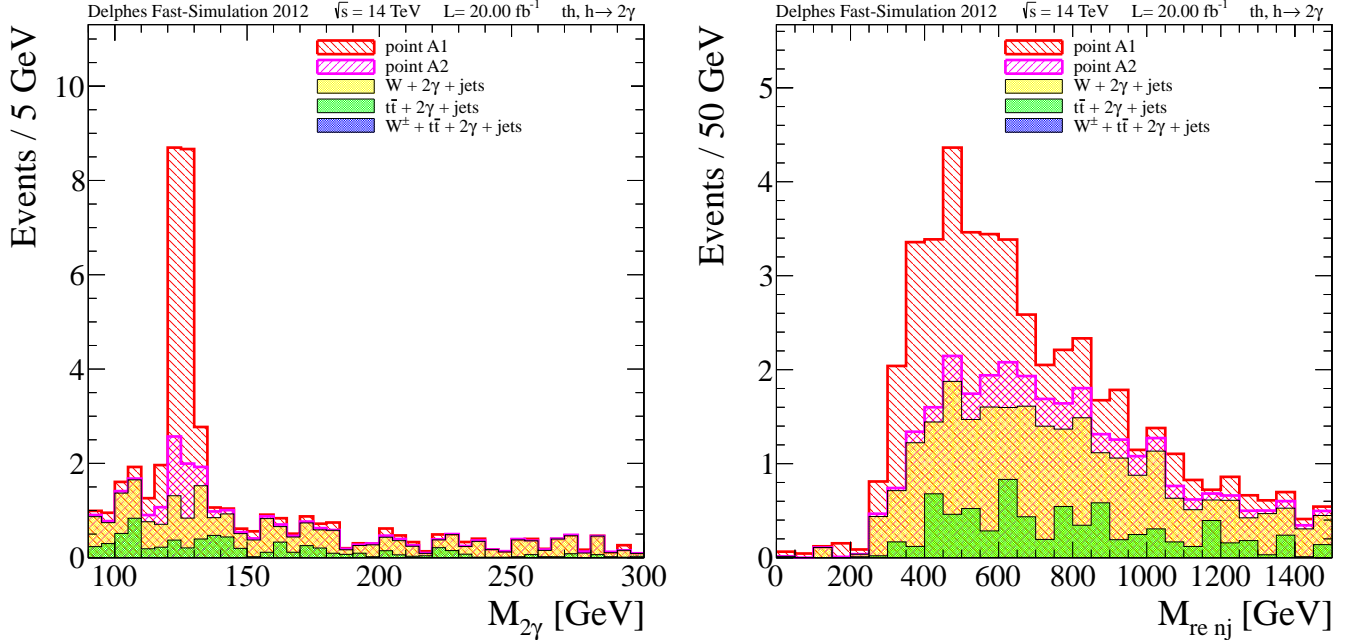


FIG. 4: Distributions of the diphoton mass,  $M_{2\gamma}$ , and of the reconstructed heavy recoil mass,  $M_{re nj}$  (see text), after all selection cuts. Signal and background distributions, normalized to the expected events for  $20 \text{ fb}^{-1}$ , are shown stacked to indicate their relative contributions. Signal distributions for points A1 and A2 correspond to a Higgs mass  $m_h = 125 \text{ GeV}$ .

## VII. CONCLUSIONS

In this paper, we have shown that there exist regions of the parameter space in beyond SM scenarios, allowed by present phenomenological and experimental constraints, in particular by the direct Higgs searches, where heavy vector-like top partner production at the LHC may give rise to new Higgs production channels, over a large Higgs mass range, extending from  $\sim 120 \text{ GeV}$  to more than  $500 \text{ GeV}$ . Indeed the SM Higgs mass exclusion, in the range between  $\sim 130$  and  $600 \text{ GeV}$ , does not hold in these beyond SM scenarios. In this context, we have also illustrated how the possible observation of a  $125 \text{ GeV}$  Higgs signal in the diphoton channel at LHC, with a cross section larger than expected in the SM, could be compatible with the presence of vector-like heavy quarks.

We have shown that for a variety of characteristic top-partner and Higgs mass values, the expected heavy top pair production cross sections and decay branching fractions lead to a signal of Higgs production (from the decay of the heavy top quark) which could be detectable at the  $14 \text{ TeV}$  LHC, with an integrated luminosity between  $\sim 20 \text{ fb}^{-1}$  and  $\sim 200 \text{ fb}^{-1}$ , over a large Higgs mass range ( $\sim 120 \text{ GeV}$  to  $\sim 550 \text{ GeV}$ ). The good diphoton and four lepton invariant mass resolution ( $\lesssim 10\%$ ), in spite of the large number of jets present in the signal events, makes the discovery possible with moderate luminosity. Finally, we have proposed new mass variables from which the heavy top mass could be estimated.

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- [98] The single production becomes dominant typically around  $m_{t'} \sim 700$  GeV as in the scenario with a singlet  $t'$  [43] or in little Higgs models [62].
- [99] Note that adding the contribution of the  $t'$  single production would increase the Higgs production rate.
- [100]  $t'$  representations (to which SM fields are promoted) with analog rate suppression effects can arise with the O(3) subgroup [20] implementable in the composite Higgs model [93, 94] and RS scenario [95, 96] which can reach strong suppressions, respectively of  $\sigma_{gg \rightarrow h} / \sigma_{gg \rightarrow h}^{\text{SM}} \sim 35\%$  and  $\sim 10\%$ .
- [101] Such a heavy Higgs would be neither SM-like, as disfavored by the EW precision tests, nor belonging to a supersymmetric extension, as forbidden by the Higgs sector structure. However, it could perfectly be e.g. in a RS scenario where its contributions to the oblique T parameter can be compensated by new KK-induced contributions.
- [102] The top quark exchange in the loop is the dominant contribution in the SM.
- [103] Similar results are expected in such a situation.
- [104] Namely the last two lines and columns of this mass matrix.
- [105] We have also checked that the Tevatron constraints are satisfied.
- [106] This number has just been updated to  $0.94^{+0.26}_{-0.34}$  for a 125 GeV Higgs [97].
- [107] The present parameters lead to a Higgs rate, for the  $WW$  channel, standing slightly outside the  $1\sigma$  range but the experimental error bars obtained by both the ATLAS and CMS Collaborations are significant.
- [108] We thank Claude Duhr and Benjamin Fuks for their precious help in this implementation.